BIOENGINEERING AND ANESTHESIA*

TERENCE W. MURPHY

Director, Biomedical Computing Facility
Associate Professor, Department of Anesthesiology

VALENTINO D. B. MAZZIA

Professor and Chairman, Department of Anesthesiology

New York University Medical Center
New York, N. Y.

INTRODUCTION

To discuss the relation between these two disciplines it is first appropriate to define them. Anesthesia is the science of inducing the relief of pain, usually for the purposes of surgical operation. Bioengineering is the application of modern technology to the biological and medical disciplines. Several factors make the union of these two disciplines a natural one: the first is that anesthesia, either by itself or in combination with the surgical operation that usually accompanies it, is a time of crisis. It is, therefore, appropriate that the patient be studied intensively not only for his own safety but also that we may learn to prevent mishaps to future patients. The three principal areas in which bioengineering contributes to anesthesia are: information gathering (transducers), information processing (application of computers), and information abstraction (conceptual manipulation). Let us consider these in reverse order.

INFORMATION ABSTRACTION (CONCEPTS)

Two conceptual approaches from technology have been applied to the understanding of the administration of anesthesia. The first of these is servo or "closed-loop" control. The second is the use of mathematical models.

Servocontrol of anesthesia is a conceptual advance which is not, as far as I know, matched in any other of the medical disciplines. The idea of the closed loop control of a process is not new, but the formalization of the concept did not occur until World War II, when it arose in

*Presented at a meeting of the Section on Anesthesia and Resuscitation, April 3, 1968.

connection with such processes as the aiming of bombs, the sighting of guns, and the automatic control of manufacturing plants. The basic principle is that a goal is set and that if the performance of this system deviates from the goal, a characteristic of the system is altered in order to oppose this deviation. Thus to maintain a constant depth of anesthesia, if the patient begins to "lighten," more anesthetic is supplied and vice versa. The mechanization or application of this idea was performed by Faulconer and Bickford,[1] who observed that the integrated, rectified activity of the electroencephalogram (EEG) was a valid indicator of the "depth of anesthesia," defined in terms of gradually increasing depression of the central nervous system correlating well with increased amounts of anesthetic agent. At that time, about 20 years ago, the following technological factors complicated the process.

1) The EEG recordings were subject to considerable artifact, especially movement artifact, and also artifact due to the drying out of electrode paste.

2) The electronic equipment then in use was barely capable of providing the large amplification necessary for the small signal; the subsequent filtration and integration were hampered thereby. (Apparently there was not then any problem in the control valves actuated by the error signal.) Although this technique eliminates one difficulty of the anesthetist, namely that of determining how deeply anesthetized the patient is, the technique never achieved utilization beyond a passing fad in some university departments.

3) The size of the apparatus required proved discouraging.

4) The average physician had a mistrust of "gadgetry," i.e., electronic or other scientific apparatus.

An engineer would ask, "Why were these problems not solved?" The answer is the reason for the development of bioengineering as a separate discipline, namely that medicine as a whole has resisted rather than promoted the introduction of technology into its domain. There should be no necessity for a separate discipline of bioengineering. It should be taken for granted that anything which could be done by engineers in other disciplines will be utilized in the struggle against disease. Unfortunately this is not so, because of the inadequacy of the medical school as an educational institution. During the past 10 years the electrode artifacts have been minimized by making better skin contact and preventing dessication of electrode jelly. Also the size of the

equipment has been reduced and its stability greatly improved by the use of transistors. These developments came about as a result of the "space race," by the application of large amounts of engineering talent and money.

This example demonstrates how anesthetists have failed to solve their technological problems and have waited for outside assistance from the field of bioengineering. Another example of this attitude occurred about 10 years ago during a clinical conference at a large metropolitan hospital, in which it was stated categorically that the cyclopropane tanks had to be closed to insure that no cyclopropane was leaking into the circuit. When it was suggested that if the valves leak this condition should be corrected by using a better valve, hands were thrown metaphorically into the air. This was about 10 years after the control valves utilized in servoanesthesia had demonstrated their ability to function successfully.

Three modalities of servocontrol have been utilized in anesthesia. The first system attempted control of muscular relaxation based upon the electromyogram (EMG) of the abdominal muscles. Specifically, it attempted to maintain a constant level of the rectified EMG by varying the rate of a succinylcholine (muscle relaxant) drip. The most probable reason for the abandonment of this modality is that the EMG is not necessarily as good a measure of muscular relaxation or the need for muscle relaxant administration as the EEG is for anesthesia, since other factors influence the surgeon's ability to gain access to his field. Consequently the dose of relaxant used was often excessive. Further, movement artifacts in these electrodes were also significant.

Servocontrol of ventilation according to Frumin *et al.*[2] adjusted the minute volume of controlled ventilation produced by a ventilator, so as to keep the end-tidal P_{CO_2} at a constant level. The abandonment of servocontrolled ventilation presumably came about because there was no consensus that a normal P_{CO_2} is necessarily the best level for the patient. There are many who believe that hyperventilation tends to promote oxygenation and reduce such deleterious effects as arrhythmias.

Servocontrol of blood pressure was demonstrated by Bellville and Seed,[3] who made use of a vasoconstrictor and vasodilator drugs administered to maintain the blood pressure at a fixed level. This modality was abandoned because blood flow is much more important than blood

pressure, and the relation between the two quantities is not simple. Also, there were problems associated with the time responses to the drugs, which produced oscillations in the system. In effect the return provided by the systems was not commensurate with the effort involved in getting them to work, particularly in view of the artifact problems discussed. Although these servomodalities were abandoned they made a significant contribution to anesthesia. The failure of the EMG and the P_{CO_2} servocontrol system demonstrated that the premises on which they were developed were inadequate. That is, other factors were important in attaining the desired goals. The anesthetist in attempting to achieve the goal must alter the therapy in response to other factors than the one controlled by the servo system. This demonstrates another important contribution of technology to anesthesia, that we can mechanize an idea, a concept, and in effect hold one variable fixed, testing the hypothesis that this is the best therapeutic approach. The failure to show this with the servocontrol systems demonstrated the importance of the other factors.

What future possibilities exist for servocontrol? One possibility would be to control very light planes of anesthesia or amnesia using eye movements as described by Mazzia and Randt,[4] perhaps by using the electro-oculogram in the same way that the EEG is used. Or, ocular position and movement could be determined using ultrasonic techniques. The roaming pupils of light anesthesia could be determined by such a technique while the eyes were closed. This eliminates the necessity of keeping the eyelids open, with consequent danger of trauma or corneal ulceration. Also, such an approach would yield a much lighter plane of anesthesia than can be controlled by the EEG, as far as we know.

Another possibility is to use a continuous cardiac output measurement to control the concentration of inhaled anesthetic during open-heart surgery.

Mathematical models in anesthesia have considerably improved our understanding of the uptake and distribution of anesthetic agents, especially with regard to the lung and the brain. The exponential nature of the rate of change of concentration in a given compartment toward the equilibrium level is understood, as is the fact that we have slow and fast compartments depending upon the body perfusion, solubility of the anesthetic agent, etc. The idea of the combination of series and parallel compartments can be used to simulate the flow of anesthetic

agent into and out of the lungs and the rest of the body. Analog computer simulations of these models are used in the teaching of anesthesia.

Information Processing (Computers)

Because of its extreme flexibility and reliability the computer—that is, the stored-program, general-purpose, digital computer—is an extremely useful tool for the control of any process, including anesthesia. If any rule in the control of the process can be stated logically, then the computer can execute that rule, given adequate transducers for input and controllers for output. The servocontrol devices are special-purpose analog computers. The advantage of the digital machine is that it can also perform a closed loop servocontrol function as required. The machines are extremely fast (their speed has increased by a factor of 100 to 1,000 over the past six years), but few situations arise in anesthesia in which this great speed can be utilized. This is primarily because of the time taken to influence physiological processes once they have started going in a particular direction. Thus to blow off excess anesthetic from the lung requires at least three breaths, or about 10 to 20 seconds; to inject the drug and allow it time to reach the organs on which it acts may take 20 seconds to one minute or more. However, the great speed of computers may be used to allow them to study many different rooms apparently simultaneously. In effect, even a relatively small computer that costs about $15,000 would have so much free time during a typical anesthetic monitoring application that it could probably monitor 10 other rooms as well. The computer cost here would have to be matched by a similar amount for transducers, amplifiers, and filters, and an equal amount for programming and engineering. We can expect that computers will become smaller and cheaper, and that their use in anesthesia and intensive care will grow.

Information Gathering (Transducers)

Technological advances have improved our ability to gather information from the patient in two ways. First, measurements can be made with less interference and, second, more important parameters can be measured. As an example of this, the last 10 years have seen the development of efficient devices for the measurement of blood flow, which is a more significant parameter than blood pressure. Also both of these measurements can now be made with less interference to normal

physiological function. Previously it was necessary to insert a catheter into the vessel in order to measure the blood pressure by use of a strain gauge, whereas now externally applied ultrasonic devices do not require arterial puncture. Similarly the electromagnetic flowmeter, a most useful device, required that the artery be exposed and forced into the electromagnetic probe, with consequent danger of trauma and coagulation. Newer ultrasonic devices are being developed which will determine blood flow by applying them to the surface of the artery, avoiding these complications.

Let us consider another field, a much simpler one: the field of acoustics. The anesthetist generally tolerates in the operating room a system which he would not tolerate in a $10 radio, much less in his own high-fidelity sound reproduction equipment. The acoustic stethoscope was designed 100 years ago and is used almost unchanged except for the introduction of the binaural listening piece. At the present time an electronic stethoscope, which can provide significant sound amplification and thereby considerably improve one's ability to determine blood pressure accurately, is available at less than $50. Such devices are probably used by fewer than five anesthesiologists in the entire nation. Obviously cost is a factor in limiting the application of technology to anesthesia, but certainly not here. The binaural stethoscope is unpleasant to wear and irritating to apply more than a hundred times a day, as is often necessary. It can easily be replaced by an ear piece such as that used in hearing aids. Again the cost is negligible; but very few have bothered to adopt this equipment. Still better would be a bone conduction device containing a miniature receiver, which would free the anesthetist from any connecting tube or cable, and also allow him to hear the other sounds in the operating room. Heart sounds, blood pressure, etc., could be transmitted to the ear-piece receiver.

What kind of advances can we expect that will be useful for anesthesia? First, continuous measurement of cardiac output would be most important for the anesthesiologist. Devices are now being developed which will allow us to determine the cardiac output on a beat-to-beat basis, either by measurement of the electrical impedance changes in the chest due to blood flow, or by alteration in the reflections of an ultrasonic wave directed at the heart. Again both of these techniques have the advantage that they do not interfere with normal physiological function and that they are applied externally. Although such

devices might not be completely accurate (errors may be of the order of 20 per cent or more), they will provide an accurate qualitative comparison; we are usually interested not in the absolute value of a particular measurement but in the changes that it undergoes in an individual during a surgical operation.

Similarly the impedance pneumograph uses changes in the electrical impedance of the chest produced by an alternating current to estimate the flow of gas into or out of the chest. Such a system is important in a monitoring application if we can insure that the chest motion does not produce artifacts.

Conclusion

We have discussed two opposing phenomena in this article, namely the contribution which "bioengineering" has made and is making to anesthesia, and the resistance to technology evinced by anesthesiologists. These phenomena are not limited to anesthesiology; they pertain also to the entire field of medicine.

The most important and valid reason for the failure of the modalities of servocontrol to become integrated into clinical practice was that the complexity of the clinical task is too great for such a relatively simple device. Now the digital computer gives us the ability to match this complexity. Any rule used clinically can be programmed into the computer and carried out unfailingly with the aid of suitable transducers. This will lead to greater quantification of anesthesia and intensive care and, as happened in the servocontrol era, the usefulness of such quantification will be evaluated easily. This should lead to a rapid growth of understanding of the complex physiology of anesthesia and intensive care.

REFERENCES

1. Faulconer, A. and Bickford, R. G. *Electroencephalography in Anesthesiology.* Springfield, Ill., Thomas, 1960. (Several references.)
2. Frumin, M. J. and Lee, A. S. A physiologically oriented artificial respirator which produces N_2O-O_2 anesthesia in man. *J. Lab. Clin. Med. 49*:617, 1957.
3. Bellville, J. W. and Seed, J. C. Personal communications, 1959 and 1968.
4. Mazzia, V. D. B. and Randt, C. Anesthesia and eye movements in the first stage anesthesia. *Arch. Neurol. 14*:522, 1966.